The Roadmap from Concept to Infusion for a Cold Survivable Distributed Motor Controller

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Abstract — **This paper will present JPL's effort working towards a distributed motor controller capable of working out in the ambient environment of in-situ missions to icy worlds such as Europa and Enceladus. Placing electronics out at the actuators has been a long-time goal for JPL because it enables a significant reduction in cable mass and its associated complexity. Learning from the previous efforts in this area we have developed a pragmatic approach based upon developing incremental deliveries that are complete products that could be sold on their own merits. These products take us closer by tackling a particular challenge by producing a tangible product that can be infused on its own long before we are ready to infuse the product that addresses our entire goal. In this paper we will discuss the goal we are trying to achieve along with the roadmap for getting there. We will present the products we have produced along with the projects that have baselined these products into their designs. We will finish by discussing our plans for the future.**

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1. INTRODUCTION

Landed missions are typically very mass constrained. Payload mass of these missions typically require a spacecraft launch mass of 7-10x the landed mass due to the required propellant to get payload to the surface. In addition, missions to ocean worlds that operate off of primary batteries or in situ generated power are power constrained as well.

Increasing science return on these missions means reducing overall mass, decreasing power used, along with increasing the volume of the payload. For mobility platforms and missions requiring robotic arms, motor drive electronics typically take up a significant percentage over the overall mass, volume and power. This reduction is the target for the work outlined in this paper.

Conventional practice, as illustrated in figure 1, is to house actuator electronics in a protected, centralized, warm electronics box (WEB), requiring highly complex, point-to-point wiring to connect the drive and control electronics to the actuators and instruments, usually located at the system appendages. The complexity of actuators used in current mission architectures require 10 or more individual wires per actuator routed individually between the centralized controller and the actuator. The Mars Science Laboratory (MSL) cables were several meters long and accounted for over 50Kg of the rover mass. Furthermore, as illustrated in figures 2 and 3, these cables represented a significant complexity for the mission, they were a significant source of thermal heat loss within the rover, they increased Electromagnetic Interference (EMI), and they increased the stiffness in the robotic arm.

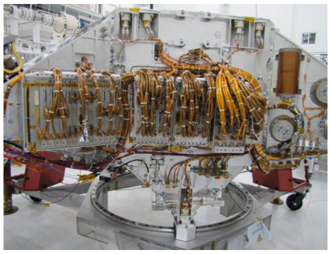


Figure 1: MSL Wiring Harness

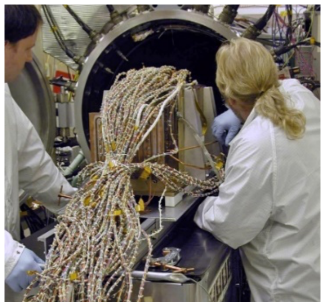


Figure 2: Integration and Test

Figure 3: MSL's Robotic Arm

As compared to current architecture implementations, placing the control and power conversion electronics at or near the actuators/instruments is the key change that lies at the core of our proposed distributed architecture. To make this change, we will develop the technology necessary to distribute the electronics and place them on a shared interface and power bus. A comparison of a motor control architecture using current state of practice versus the distributed solution is shown in figure 4 and 5. Each actuator to controller wire shown in figure 4 represents 20 wires routed individually to each actuator, representing 0.8Kg of cable mass per motor. Figure 5d illustrates the reduction in cable mass and complexity when each motor has distributed control and power electronics and is connected to a shared power and control bus.

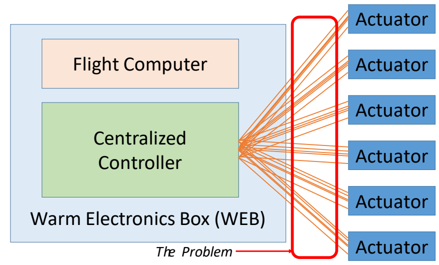


Figure 4 Current state a practice: Point to point wiring

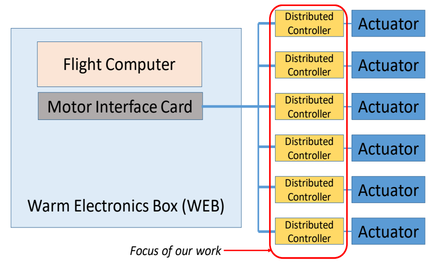


Figure 5 Distributed Motor Control Electronics

2. Benefits of Distributed Motor Control

Distributed motor control eliminates the point-to-point wiring, and reduces the wire count by two orders of magnitude with concomitant savings in mass, cost and complexity. Additional benefits include:

- Minimization of thermal losses by minimizing cables leaving the warm compartment.
- Greatly improved noise immunity, and reduced EMI which results in improved actuator control and repeatability.
- Improved modularity. With distributed motor control it is easy to add motors to the system. This is done by adding additional nodes to the network.

Table 1 provides a comparison of historical actuator cable mass versus the proposed implementation. This study showed that actuator harness mass represents 25 - 33% of the total harness mass. Distributed motor control will reduce the actuator harness mass by 90% to 1.8Kg. [1,2]

Rover System	Pathfinder	MER	MSL	MSL w/DMC	Benefit
Total Wiring Mass	1.4 Kg	10.4 Kg	52.7 Kg	37 Kg	35.2 Kg (90%) reduction in actuator harness mass
Actuator Wiring Mass	0.35 Kg	3.0 Kg	17.4 Kg	1.8 Kg	
Percentage of Actuator Harness Mass	25 %	29 %	33 %	5 %	

Table 1: Benefits of a Distributed Motor Control (DMC)

3. Challenges to Distributed Motor Control

In order to achieve the benefits of distributed motor control, new technologies need to be developed. This is particularly true in a space environment. The challenges include:

1. **Localized control**: In order to allow motors to hook together through a common communication interface, some amount of localized control of the

motors is needed. The more control that is done locally the lower the bandwidth requirements on the interface bus. This control will at a minimum include commutation, rate determination, and telemetry collection.

2. **Communication Network:** The motors all need to connect over a common interface network. This network potentially needs to bridge fault containment and grounding boundaries.
3. **Survive In the Extreme Environment:** Since the electronics are out at the actuators, the distributed electronics needs to be able to survive the thermal and radiation environment. Temperature survivability means addressing operation and thermal cycle survivability. Another more traditional method is to provide survival heaters.
4. **Operate In the Extreme Environment:** Operation in the environment can be tackled in two ways. The first is to design electronics capable of operation in the environment. In the case of ocean world missions this temperature can be quite cold: -180C. The other method, focuses on survival. Here we keep the electronics cold when they are not in use, but heat them prior to operation.

4. Past and Current Distributed Motor Control Efforts

There have been two past efforts at JPL aimed at developing a distributed motor controller. The first effort was called the Distributed Motor Controller. This technology effort was aimed at JPL's mobility missions and relied heavily on discrete devices miniaturized through the use of advanced packaging techniques. The second effort at JPL built upon the original DMC effort, but focused on reducing part count through the use of an analog Application Specific Integrated Circuit (ASIC). The third effort, and the primary subject of this paper, is aimed at Europa and ocean world mission. This Europa Lander Motor Controller is based upon standardized components miniaturized through advanced packaging, but the focus in on surviving the environment but not operating at extreme temperatures. We will discuss each of these approaches in detail, contrast them, and discuss what we can learn and inherit from them. We will then discuss the roadmap that we developed for the Europa Lander Motor Controller in the following sections.

5. DMC1 Original Distributed Motor Control Effort

The DMC1 effort was aimed at JPL's MSL mission. This effort successfully demonstrated a distributed motor controller capable of surviving and operating in the Martian environment. This controller had to meet a 100Krad Total Dose requirement along with a requirement to survive from -180ºC TO +115ºC and operate from -180ºC TO +85ºC. In addition, the controller needs to survive 500 cycles on the surface of the planet. [3] This controller made use of standard of the shelf radiation hardened components that were tested and found to operate at the required temperatures. The controller's ability to wrap around the motor assembly was made possible through the use of chip on board technology. [4]

Although this effort successfully demonstrated that they could meet their requirements the MSL project proceeded with a lower risk centralized motor control solution. The lessons learned from the electronics effort along with the electronics packaging survivability effort were fed forward to future technology efforts including the Europa Lander Motor Controller.

Figure 6: DMC1 Original Distributed Motor Controller

6. DMC2 Extreme Environment capable Distributed Motor Controller

JPL's second effort at distributed motor control built upon the first. The original DMC employed more than 1170 components and had a high manufacturing cost. The second effort focused on simplification of the design of the original DMC by reducing its component count, hence reducing the manufacturing cost, mass, and power consumption, and thereby making it more suitable for flight systems. This architecture, as illustrated in figure 7, differs from the original DMC as follows:

(a) Definition of an optimized partitioning between the "low-temperature-resident" distributed portion of the design, and the "warm-resident" section;

(b) Elimination of extraneous, little used, functions;

(c) Utilization of a low-temperature-resident analog ASIC

This design was built to both survive and operate on the Martian surface. Communication with the host was done over a fault tolerant serial bus. The device was packaged, as shown in figure 8, to fit within a compact 9.5cm x 4.4cm x 1.5cm package. [1,7]

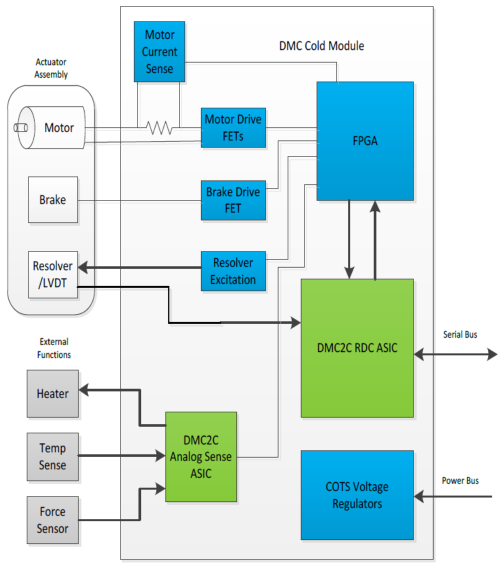


Figure 7: DMC2 Extreme Environment Capable Distributed Motor Controller Block Diagram

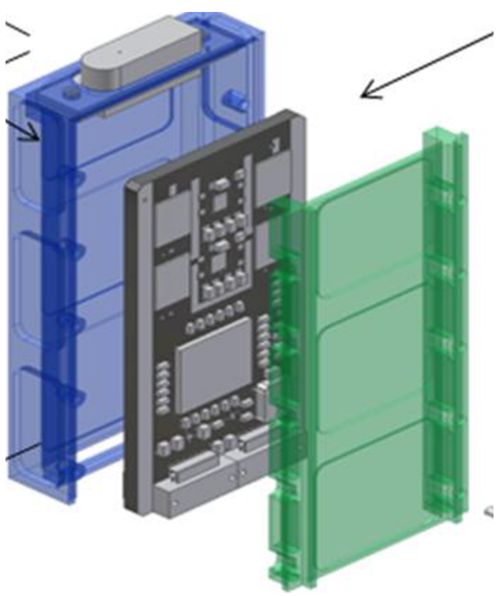


Figure 7: DMC2's Compact Packaging Concept

This effort that they had a feasible concept, demonstrated a prototype of the device, proved cold operation of their FPGA, and demonstrated key components of the analog ASIC. Despite the successes mentioned, the MSL project proceeded with a lower risk centralized motor control solution. The lessons learned from the electronics effort along with the electronics packaging survivability effort were fed forward to future technology efforts including the Europa Lander Motor Controller.

7. Comparison of the Past Efforts

The prior efforts all produced a lot of good work but failed to infuse their technology into their targeted missions. Both of these efforts focused on developing a motor controller that was both capable of cold temperature survival and cold capable operation.

The cold capable survivability was achieved through advanced packaging technology and the proper selection of attachment methods capable of surviving deep temperature cycles. The work in the efforts has shown that cold survivability can be achieved.

The DMC1 and DMC2 had different approaches to cold operation. The first effort, DMC1, focused on finding of the shelf radiation hardened components that were found to capable of operating at cold temperatures. This forced a large component count because most integrated solutions were found to be not capable of cold operation. The use of more primitive components drove up the parts count and packaging complexity. The second effort, DMC2, was still focused on operation in the cold. This developed a custom analog ASIC as their way of reducing parts count. This drives up the cost, and the risk, of dealing with changes in requirements.

8. Our Pragmatic Strategy

As shown in the table of requirements below, both DMC1 and DMC2 tried to tackle cold survivability and cold operation. Both DMC1 and DMC2 met the packing goal through a combination of advanced packaging and ASIC technologies. This was handled in two different ways. In light of the two previous efforts we have developed a strategy that leverages the work from before but focuses less on cold operation, and more on advanced packaging. The goal is to make our electronics small enough that the amount of energy and time required to heat them to a normal operating temperature is minimized. This allows us to use conventional radiation hardened electronics operating within its normal range of operation.

	Localized Control	**Comm. Network**	**Survival temp.**	**Operating temp**
DMC1	Digital ASIC	Differential Multi-Drop Bus	-180ºC TO +115ºC	-180ºC TO +85ºC
DMC2	Digital ASIC/FPGA	Galvanically Isolated Bus	-135ºC TO +85ºC	-135ºC TO +85ºC
Europa Lander	RTG4 FPGA	Galvanically Isolated Bus	-184ºC to 85ºC	-55ºC to 85ºC

Table 1: Contrast of DMC Efforts

9. Roadmap

The following figure illustrates our plan to getting to a distributed motor controller. Our goal is to get to a cold survivable motor controller that is capable of meeting the challenges mentioned in section 3 of this paper. From the DMC1 effort we will build upon the Thermal Cycle Tolerant Electronics (TCRE) [3] design rules to design electronics capable of meeting the temperature extremes. We will build upon the FPGA code along with the communication network developed under DMC2. Rather than develop a singly packaged product as we did in the past we will develop standardized modules. These modules represent the major components of the motor controller. The electronics design can be portioned so that the modules can be used together to implement a motor controller, or used by themselves for other applications beyond motor control.

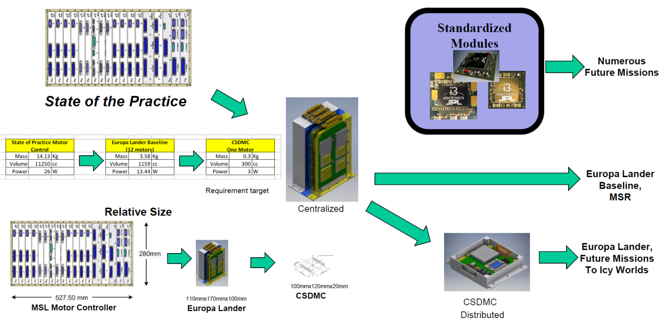


Figure 8: Europa Lander Motor Controller Roadmap

The electronics design can be portioned so that the modules can be used together to implement a motor controller, or used by themselves for other applications beyond motor control. Our infusion distributed motor control, currently takes to steps. We will be first developing a centralized motor controller. This centralized motor control will be a step towards a distributed solution in that it will have a serial communication network that meets our distributed network's requirements and that the motor control cards will be constructed of standardized modules capable of cold temperature survivability. The next step will be a cold survivable distributed motor controller [5] developed from these modules.

10. Standardized Modules

Figure 6 provides a more detailed view of the architecture with an expanded Cold Survivable Distributed Motor Controller (CSDMC). Our architecture optimally divides motor control between the warm box computer, which performs all mission dependent functions including control loop closure and associated algorithms, and the cold module which provides the motor and sensor interface, analog/digital conversion, and commutation. This architecture minimizes the number of components residing in the cold module, thus minimizing cold module mass, volume, cost and risk. The highlighted areas in Table 2 outline the work covered under our NASA COLDTECH funded activity. This work addressed the radiation and temperature survivability of existing electronics along with developing the remaining reduced Space, Weight and Power (SWaP) building blocks of the distributed power conversion system, i.e., point-of-load regulator and isolated converter.

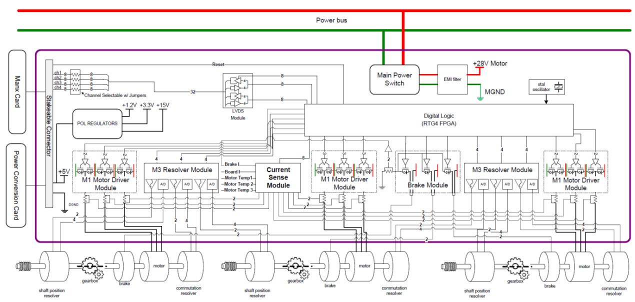


Figure 9: Europa Lander Motor Controller Diagram

Our motor controller is constructed of modules developed under NASA and JPL internal investment. As illustrated in Figure 8 the following modules were developed:

1. Motor Driver Module: This module implements a 3-phase H-bridge for driving the motors. This module is currently capable of drive 3A motors.
2. Resolver Module: This module is able to interface with three resolvers. These resolvers are used for motor commutation and output position sensing.
3. Current Sense Module: This module allows for the sampling of motor phase currents.
4. LVDS Module: This provides a standardized interface to the spacecraft flight computer. [6]
5. POL Module: This module implements point of load regulation. One module is needed for each of the three different voltages that are needed locally on the CSDMC.
6. Isolated Converter Module: This module provides for the DC to DC conversion needed to provide an isolated power system for the CSDMC.

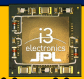
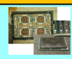
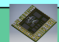
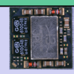
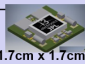
Technology	Picture	Heritage	Function
Motor Driver Module Other uses: Brushed Motors, Solinoid driver	 3.0cm x 3.0cm	GCD – Ultra Low Temperature Electronics	Power stage for driving motors
Resolver Module Other uses: LVDT, Strain Guages	 3.5cm x 3.5cm	GCD – Ultra Low Temperature Electronics	Position sensing
Low Voltage Differential Switching (LVDS) Module Other uses: SpaceWire	 1.5cm x 1.0cm	JPL Internal R&TD funding	Motor control card to central computer interface
Current Sense Module	 2.1 cm x 2.1 cm	Europa Lander	Current and temperature sensing
Point of Load Regulator Module Other uses: Linear regulator replacement	 1.7cm x 1.7cm	NASA Coldtech	Local power conversion
Isolated Converter Module	 1.7cm x 1.7cm	NASA Coldtech	GaN FET driver

Figure 10: CSDMC Advanced Packaged Modules

Although the modules were developed with a distributed architecture in mind, they can be used to make a centralized architecture more mass/volume efficient. For example these modules can be tiled together onto a more conventional 6U card capable of controlling multiple motors.

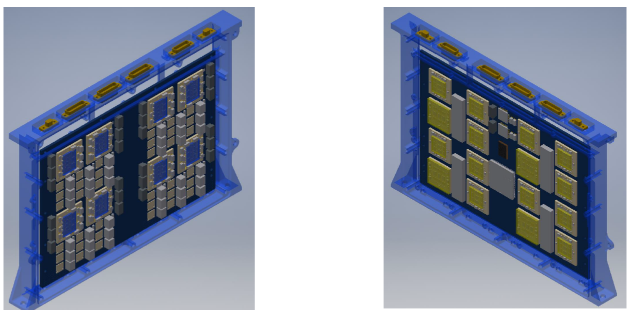


Figure 12: Modules used in a 6U configuration

11. Centralized Solution: Motor Control Card

For the centralized application we have developed a 10cm x 16cm card. Each motor card can control up to three motors. Only one motor can run at a time per card. Our design allows for the position of each motor to be monitored by two resolvers, one motor shaft and one on the output of the gear box. Each resolver module can talk to 3 resolvers. Each card has two resolver modules. Each card has 2 resolver channels per motor. One for commutation and one for output position. Six in total. All can be running at any given time. There are four motor cards in the stack. This gives a total of 12 motors, and 24 resolver channels.

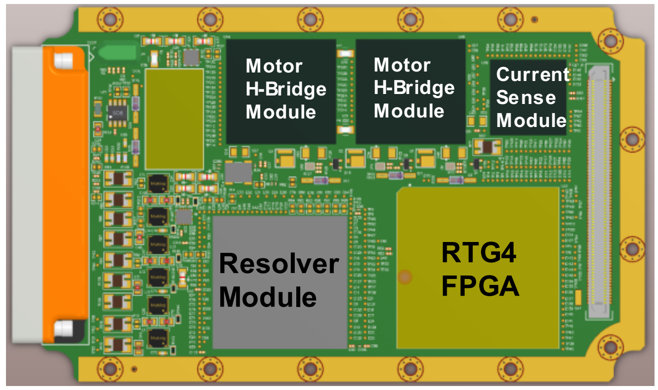


Figure 13: Front Side of Europa Lander Technology Maturation Motor Control Card

12. Future Plans

Under Europa Lander technology maturation funding, we will be developing a centralized motor controller. In the future we would like to take the next step and develop the distributed CSDMC. The packaging for the CSDMC allows for a compact package size of 10cm x 10cm x 3cm. This compact size allows for the motor electronics to be packaged at the actuators. The electronics is small enough to fit with the structure of robotic arms or to be packaged along with the actuators. An illustration of our packaging approach is shown in figure 19 and 20.

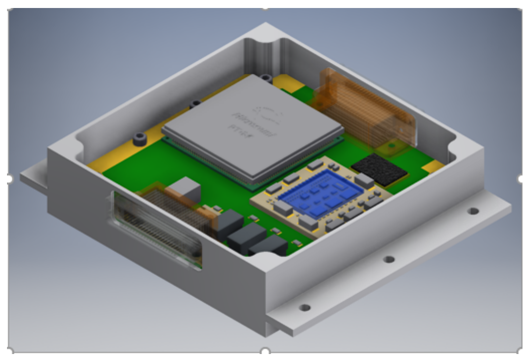


Figure 13: Cold Survivable Distributed Motor Controller

13. Summary

In this paper will discussed JPL's effort of working towards a distributed motor controller capable of working out in the ambient environment of in-situ missions to icy worlds such as Europa and Enceladus. We hope that our pragmatic approach will get us to our goal of placing electronics out at the actuators has been a long-time goal for JPL because it enables a significant reduction in cable mass and its associated complexity. Learning from the previous efforts we have developed an approach based upon developing incremental deliveries that in themselves are complete products that could be sold on their own merits. These products will tackle a particular challenge by producing a tangible product that can be infused on its own long before we are ready to infuse the product that addresses our entire goal.

14. ACKNOWLEDGEMENT

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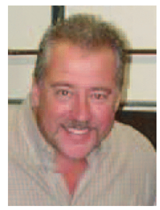
17. BIOGRAPHY

Gary Bolotin received a M.S. in Engineering from University of Illinois at Urban Champaign in 1985 and a B.S. in Engineering from Illinois Institute of Technology in 1984. He has been with JPL for more than 32 years. He is currently the lead of the Europa Lander Motor Controller. He has also managed engineering teams as both team leads and line manager at the section and group level,



Don Hunter has been with the Jet Propulsion Laboratory and member of the Advanced Electronic Packaging Engineering section since 1993. Major contributions include; development of ruggedized 6U-VME fight system design for the Mars Pathfinder Mission, holds several Cal Tech and US Patents for work in advanced packaging systems architectures He holds a B.S. in mechanical engineering/Industrial Design from California State University Los Angeles and has been involved in the electro-mechanical packaging environment for over 28 years. He possesses experience ranging from commercial applications of deck top test equipment to military (DOD) cold temperature and high-G integrated packaging applications.

Chris Stell holds a Bachelor of Science in Engineering degree from California State University Northridge (May 1986). Is a Principal Engineer at the Jet Propulsion Laboratory and employed since 1992. He has over 30 years experience designing power electronics for space applications.

Malcolm Lias holds a B. S. in Electrical Engineering from Rochester Institute of Technology. He is currently developing Motor Control Card for Europa Lander at Jet Propulsion Laboratory (JPL). Testing and documenting the Distributed Motor Control Multi-Chip Module for use on the Europa Lander. Prior to joining JPL, Malcom worked for Wordword Inc where he was responsible for design, product support, and testing of control electronics for missiles, smart bombs, and aircraft.

Ben Cheng is currently an intern at JPL. He will be graduating from California Polytechnic Pommona in the spring of 2019.

Upon graduation, he will be joining the JPL Motor Control team full time. His course work includes Control Systems; Digital Signal Processing; Programming Languages; Digital Logic Design; Microcontrollers; Filter Design; Multivariable Calculus; Differential Equations and Linear Algebra. Prior to joining JPL, Ben was the Computer Aided Design Lead Team for the Sprocket – FIRST Robotics team. In addition he was the curator for the MAG Laboratory at Cal Poly.